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# Development of a Multi-Layer Guided Wave Inspection Technique

*M. Quarry, D. Chinn, T. Hay*

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# DEVELOPMENT OF A MULTI-LAYER GUIDED WAVE INSPECTION TECHNIQUE

Mike Quarry
Diane Chinn

Thomas Hay, Penn State University

# INTRODUCTION

This study investigates the inspection of a particular layer of a multi-layer structure using ultrasonic guided waves. Techniques based on Lamb waves have been developed for the inspection of plate structures and are well understood. Guided waves also exist in multi-layered plates as well. Energy distributions vary across the thickness of a multi-layer structure depending on the mode and frequency. Hence, a potential way to inspect the bottom layer of a structure is to find modes with sufficient energy in the bottom layer.

Fig. 1 shows the composition of a 4-layer plate. The materials were pressed together. Table 1 shows the materials properties of layers. It is desired to inspect the bottom layer of this structure with access limited to the top surface. Guided waves with significant energy in a given layer can penetrate into and propagate in hidden layers. Any particular layer could be inspected by exciting a guided wave mode in the multi-layer that has sufficient energy in the layer of interest. Pulse echo and through transmission techniques may provide valuable information about the mechanical integrity of structure.

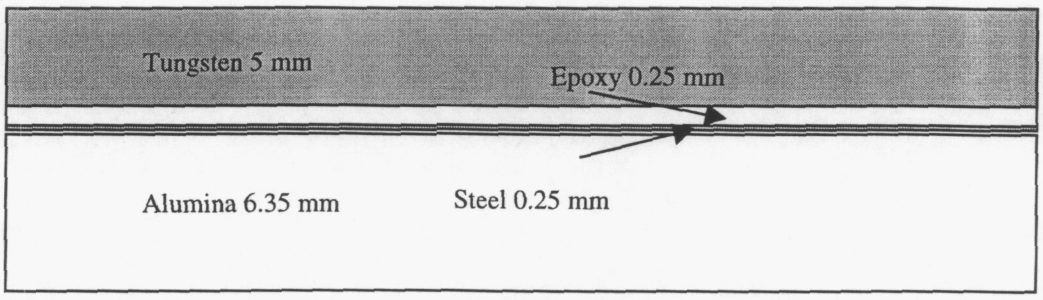



Figure 1. A diagram showing the structure of a 4-Layer specimen.

Table 1. Layer Material Properties

| Layer | Density ($kg/m^3$) | Longitudinal Velocity (m/s) | Shear Velocity (m/s) |
|---|---|---|---|
| Tungsten | 19200 | 5200 | 2900 |
| Epoxy | 1100 | 2700 | 1100 |
| Steel | 7900 | 5900 | 3200 |
| Alumina | 3990 | 11100 | 6040 |

# METHODOLOGY

Dispersion curves for the multi-layer structure are computed by determining the roots of the dispersion relation for the given structure. Phase velocity dispersion curves are shown in Fig. 2, and group velocity dispersion curves are plotted in Fig. 3. Phase velocity dispersion curves supply the physical characteristics that must exist for modes to exist in the structure. This information is utilized for the generation of ultrasonic guided waves. Group velocity dispersion curves describe the speed at which each mode propagates and enables the localization of any flaws in the structure.

Some important properties of the modes should be mentioned here. Each point on the dispersion has a unique displacement pattern across the thickness of the structure. As a result, each mode has different properties as it propagates in the structure. Some modes have a lot of energy in the bottom layer, while some have very little. Inspecting the bottom layer requires a mode to have at least a sufficient amount of energy in that layer. Modes with these characteristics must be found and excited to develop a successful inspection technique.

Sample displacement patterns are shown in Fig. 4. Modes consist of two components of displacement. On e is in the direction of propagation, and the other is transverse to the propagation direction and normal to the top and bottom surfaces. In Fig. 4, U1 is in the direction of propagation, and U2 is normal to the outer surfaces. These patterns demonstrate the differences in energy patterns that can exist between modes. For example, the mode shown in Fig. 4a would be a suitable mode for inspecting the bottom layer, while the mode in Fig. 4b would most likely be ineffective.

When a mode encounters a disturbance to the waveguide structure, such as a crack or loss of wall thickness, the mode is reflected back to the transmitter. Thus, a crack in the bottom layer could be detected in a pulse-echo setup using a suitable guided wave mode. Another approach would be to use a transmitter and a receiver at two ends of the structure. Here, a crack would reduce the amount of energy received at the receiver. Larger cracks would produce larger losses in energy.

Exciting and generating desired modes can be performed through probe design. Two methods for controlling and exciting guided waves are angle beams and arrays. Angle beams are generally cheaper and easier to construct, so they have been chosen for this study. Variable angles beam probes were used with a longitudinal wave transducer with a Plexiglas wedge material. A variable angle beam excites a mode with a narrow spectrum of phase velocity centered around a value given by Snell's Law in Eq. (1). $\theta$ represents the incident angle of the transducer.

$$V_{ph} = \frac{V_{wedge}}{\sin\theta} \qquad \text{Eq. (1)}$$

A tone-burst drives the transducer with a narrow frequency spectrum. Modes are searched by sweeping the angle of incidence and frequency. Each angle of incidence and frequency is an experiment of itself. The searching of modes identifies the best mode candidates for the particular inspection application.

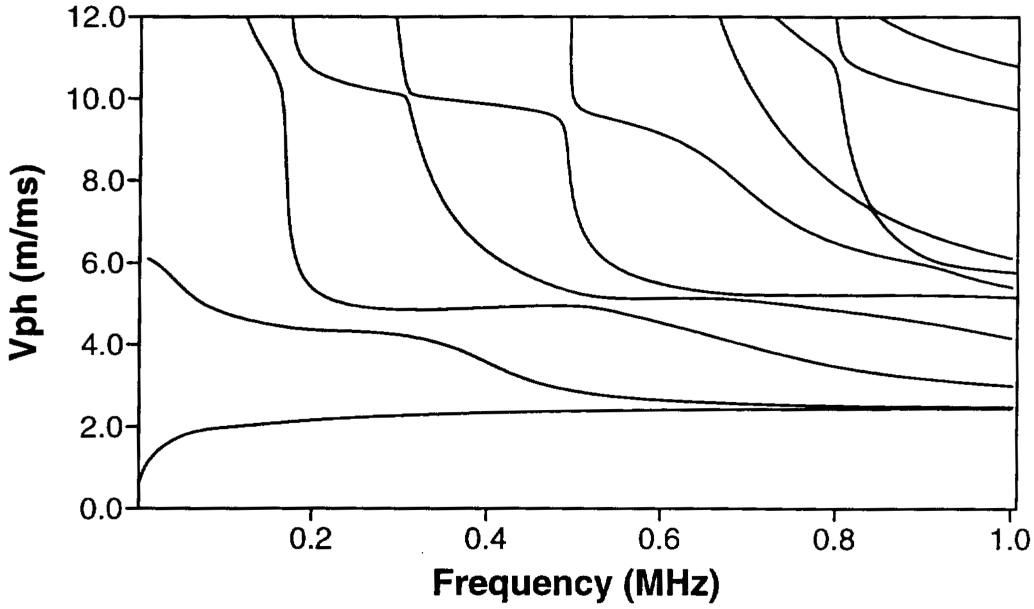



Figure 2. Phase velocity dispersion curves for the 4-layer plate.

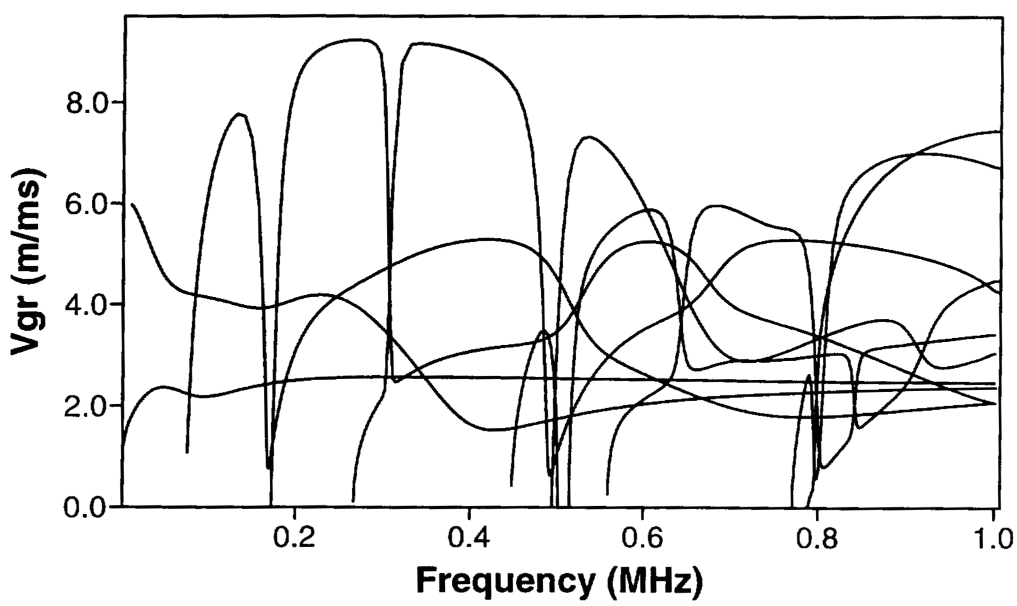



Figure 3. Group velocity dispersion curves for the 4-layer plate.

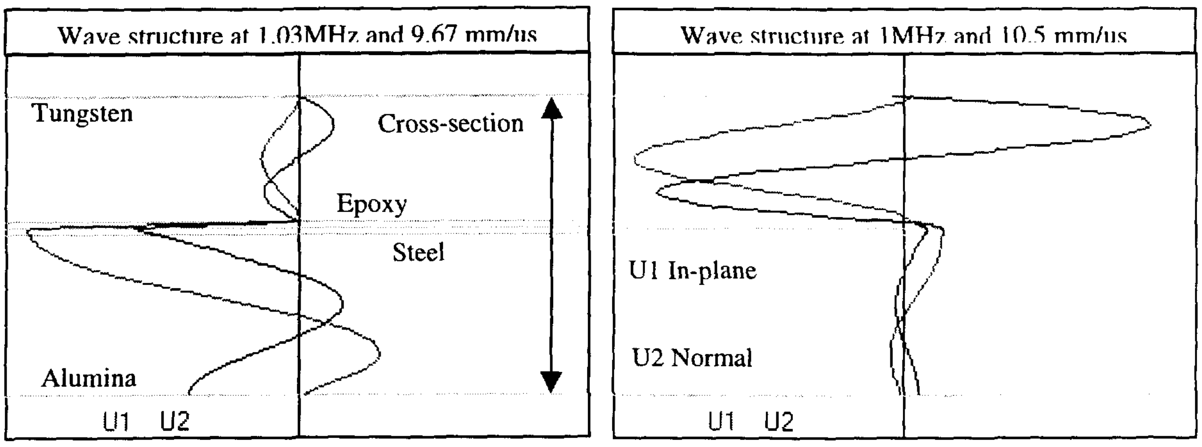



Figure 4. Sample displacements showing differences in wave structures of guided wave modes in the 4-layer structure.

## EXPERIMENTAL RESULTS

Two specimens were prepared for this study. The dimensions of the specimens were 4" wide by 9" in length. One contained the 4-layer structure with no flaws, and the other had a crack in the alumina layer. The crack was several inches wide and penetrated through to the steel layer. The specimens were made by clamping the layers together using C-clamps. The two specimens shall be referred to as the specimen without a crack and the cracked specimen.

Both specimens were tested in pulse echo and through transmission setups. Pulse echo setups are useful when a flaw that creates a strong reflection, such as a crack. Through transmission setups generally have greater sensitivity when flaws have a long length along the propagation direction but still have potential use for detecting cracks.

Fig. 5 illustrates the pulse echo-concept using guided waves. Using an angle beam transducer, ultrasonic energy is coupled into the top layer first and then penetrates into the subsequent layers. At the right phase velocity and frequency, a guided wave mode will propagate in the structure. Modes propagating in the structure will be reflected at the edge of the plate and at the crack in the bottom layer.

In the through-transmission mode, a guided wave is excited by the sender and received at the receiver. Fig. 6 shows a schematic of the setup. Two attractive features of through transmission data are amplitude and time of arrival. Amplitude can be reduced as a result of a flaw in the structure. Time of arrival may also be changed as a result of changes in group velocity that can be caused by flaws in the structure. Again, each mode will behave differently based on its properties of power flow, displacement pattern, wave number, and dispersion.

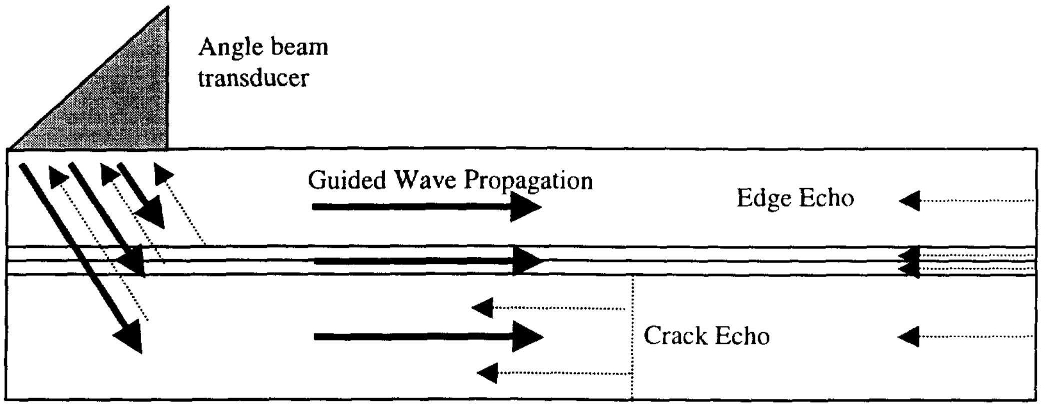



Figure 5. Guided wave pulse-echo setup

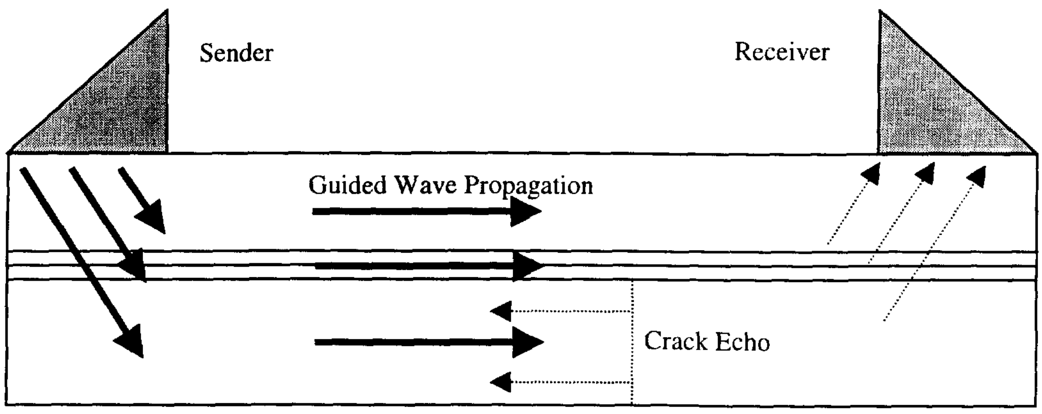



Figure 6. Through-transmission setup

By sweeping frequency at various phase velocities modes with significant energy in the bottom layer were found and used for crack detection. Many other modes were found to be insensitive or produced too much noise for inspection purposes. Modes were verified identified by confirming the group velocity with the curves shown in Fig. 3. Fig. 7 shows an RF waveform obtained from the structure with the cracked bottom layer at a frequency of 0.9 MHz and a phase velocity of 5440 m/s. The echo from the crack occurs at approximately 80 μs and that from the edge of the structure occurs at approximately 144 μs. The echo from the crack was verified by damping the structure by pressing one's fingers on the surface before and after the crack. Damping before the crack reduced amplitude of the crack and the edge echoes while damping after the crack only reduced the amplitude of the edge echo.

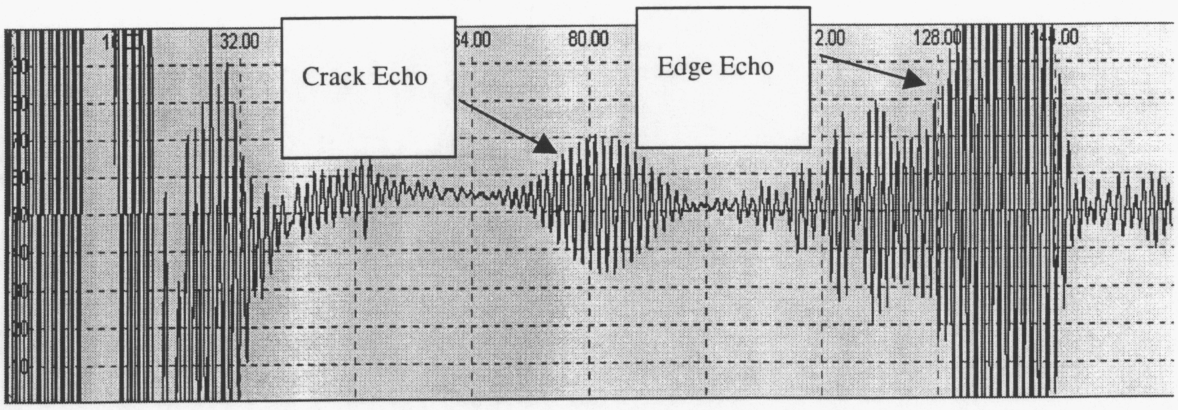



Figure 7a. Sample RF waveform from cracked structure of a mode with frequency of 900kHz and phase velocity of 5.44 km/s.

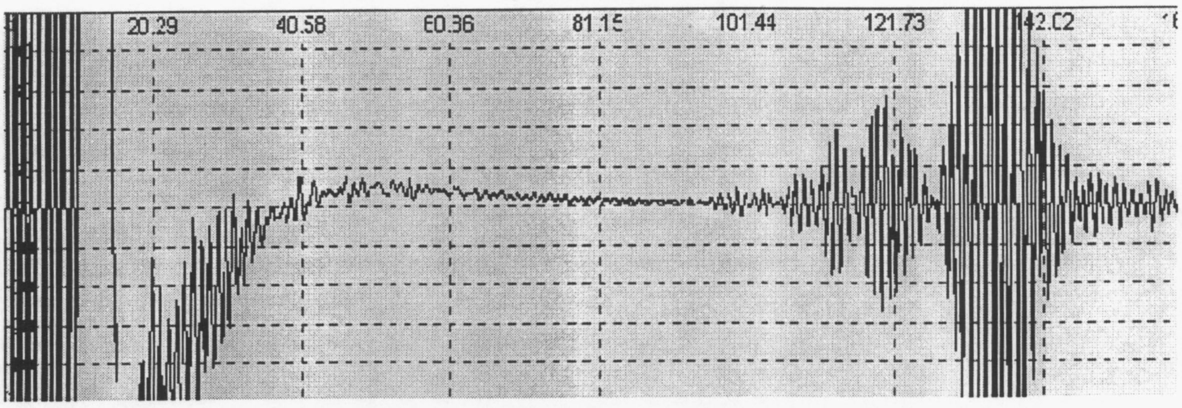



Figure 7b. Sample RF waveform from a specimen with no crack.

Fig. 8 shows the power flow in the direction of propagation for the mode shown in Fig. 7. The power flow is a product of the velocity vector and the stress tensor of the wave as given in Eq. 2 as

$$\vec{P} = \frac{1}{2}\left(\vec{v} \cdot T\right) \qquad \text{Eq. (2).}$$

The power flow explains why this mode is sensitive to flaws in the bottom layer. The distribution of the power flow is weighted in the bottom layer, but there is still enough energy at the surface for the sensor to detect the mode.

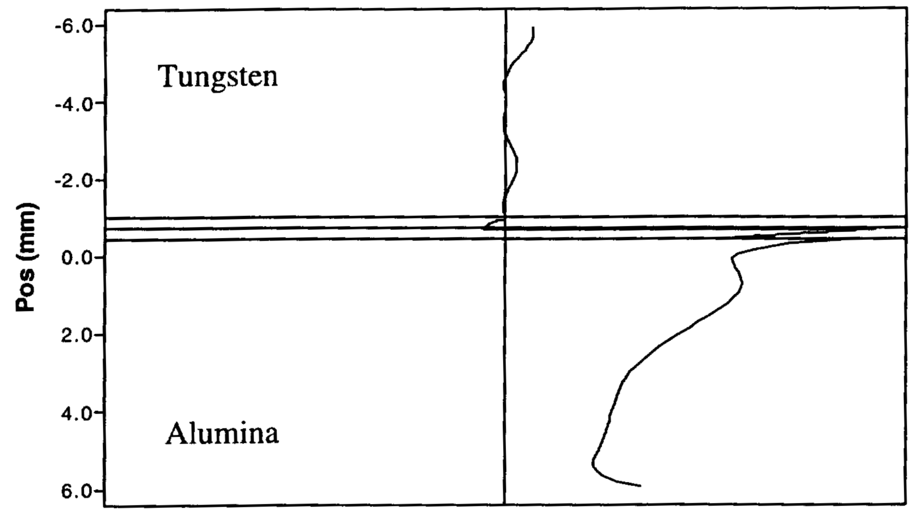



Figure 8. Plot of the power flow in the direction of propagation a mode with a frequency of 900 kHz and a phase velocity of 5.44 km/s.

Fig. 9 shows a sample RF waveform showing the detection of the crack in the 4-layer specimen. The mode has a frequency of 495 kHz and a phase velocity of 5.4 km/s as determined using Snell's Law in Eq. 1. Fig. 10 shows a plot of the power flow in the direction of propagation for this mode. The power flow is strongest in the bottom layer, which suggests that this mode is suitable for inspecting the bottom layer.

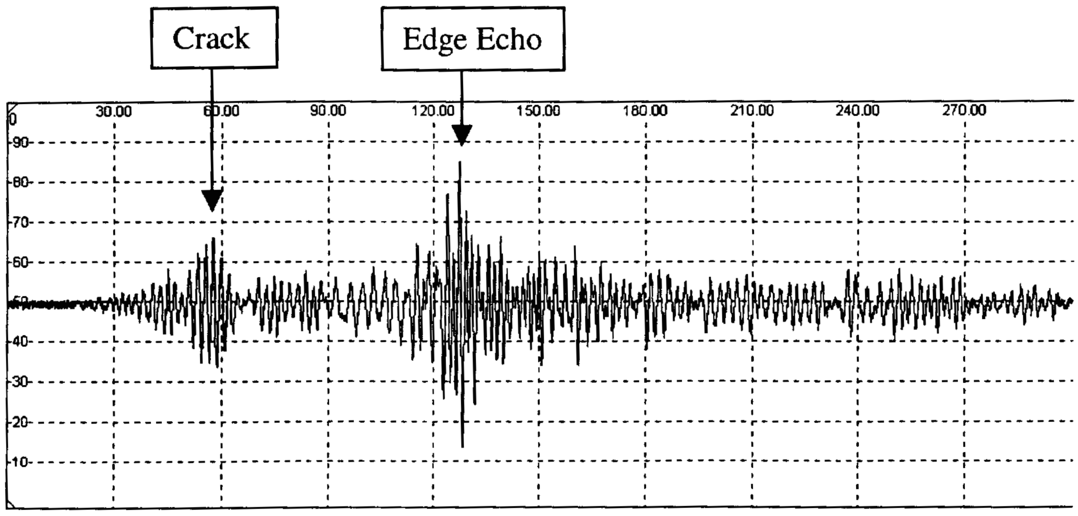



Figure 9. A sample RF waveform showing the detection of the cracked specimen.

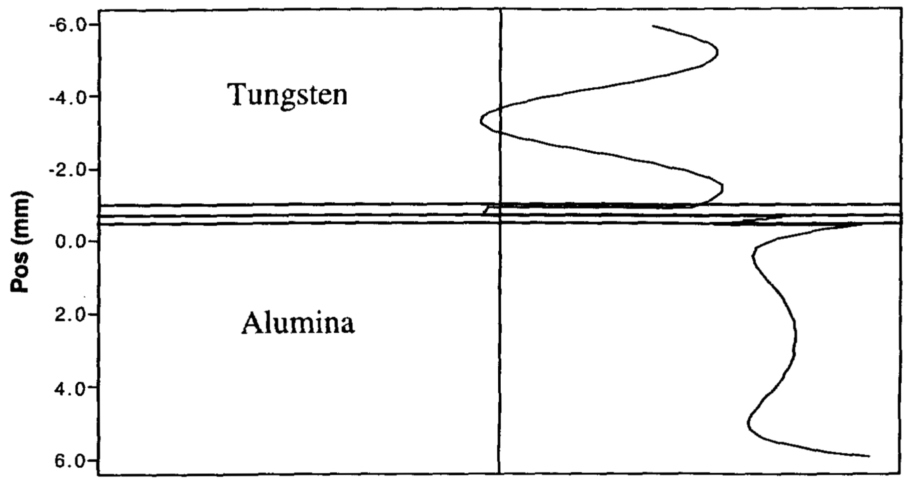
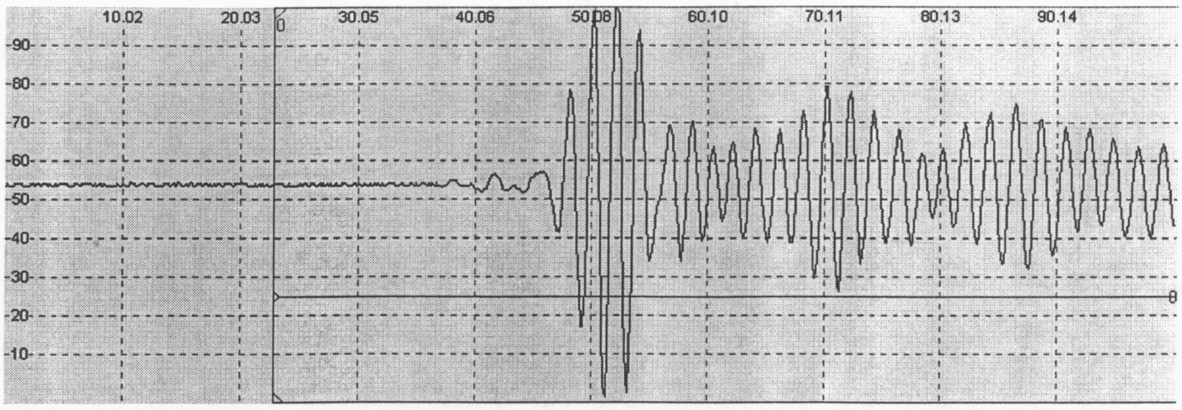


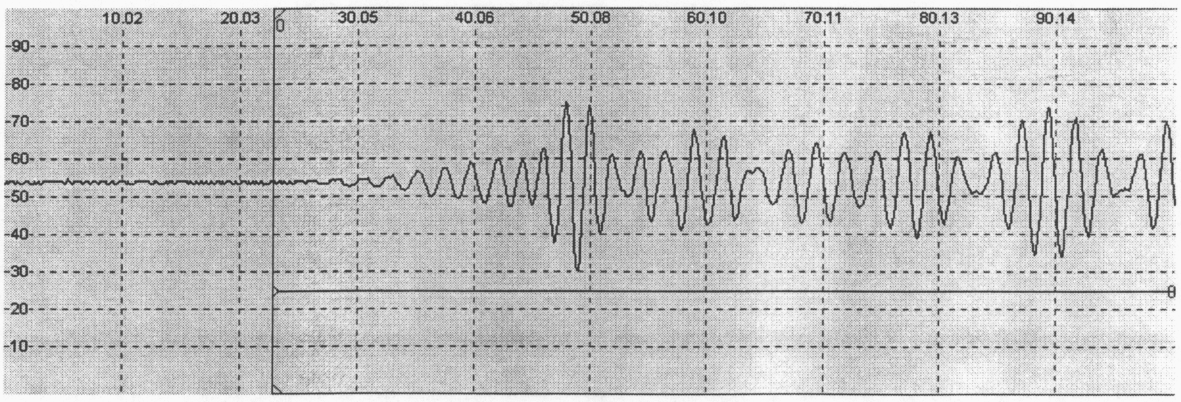

Figure 10. Plot of the normalized power flow in the direction of propagation as a function of thickness for Mode 2 at 495 kHz.

The two modes described in Fig. 7 and Fig. 9 emerged as the best candidates based on experimental results for inspecting the 4-layer structure in a pulse echo setup. Theoretical computations on these mode's properties confirm that they have properties suitable for inspecting the 4-layer structure.

Through transmission experiments were also conducted with some success as well. Fig. 11 compares the through-transmission RF waveforms as received from the structures with and without a crack. Fig. 11a shows a mode at 545 kHz, and Fig. 11b shows the signal as received from the structure with a crack in it. As can be seen in Fig. 11b, a reduction in amplitude occurs as a result of the crack. In general, the amplitude of the received mode will be lower in a cracked structure relative to a mode propagating in an uncracked structure since a portion of the wave is reflected at the crack. The magnitude of amplitude loss is dependent on the mode's properties. This mode has the potential to interrogate the bottom layer for potential damage. There is also a slight change in group velocity. Fig. 12 shows this mode's group velocity curve, which is dependent on the frequency times thickness product. The slight change is likely because the mode at 545 kHz is in a fairly dispersive portion of the curve.




a) Through transmission signal at 545 kHz on specimen with no crack.




b) Through transmission signal at 545 kHz as received on the cracked specimen.

Figure 11. RF waveforms of through transmission setup of a guided wave mode at 545 kHz and received at an angle of 30 degrees.

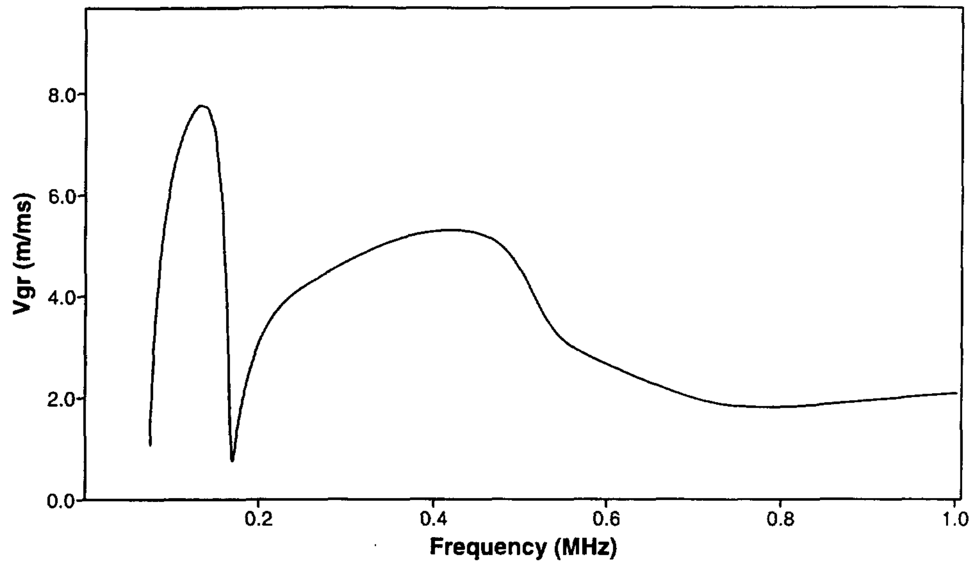



Figure 12. Group velocity dispersion curve for the mode shown in Fig. 11.

## CONCLUDING REMARKS

Guided waves were successfully used for crack detection in a 4-layer, tungsten-epoxy-steel-alumina structure. Pulse echo and through transmission setups have potential, but the pulse echo setup would likely be more sensitive for detecting cracks. Placing a sensor on the bottom of the structure was able to confirm that energy is propagating in the bottom layer, which establishes a basis for inspecting the structure for damage. Theoretical computations support the hypothesis that the mode must have sufficient energy in the layer of concern for flaw detection. The concepts for inspecting multi-layer structures discussed in this work may also be applied to any variety of multi-layer structures. The success of this study demonstrates a proof of principle for using the technique on other layered structures.